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Outdoor W-Band Hybrid Photonic Wireless Link Based on an Optical SFP+ Module

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***Abstract*—This letter proposes a W-band hybrid photonic wireless link based on a commercial SFP+ module and experimentally demonstrates its performance. Using a free running laser as local oscillator and heterodyne photonic upconversion, good frequency stability is achieved. Outdoor wireless transmission over 225m with a BER below 10^{-6} is demonstrated and the maximum reach of the system with typical RF components is calculated, finding wireless distances above 2km to be feasible. Being based on a commercial SFP+ the proposed hybrid photonic wireless link offers seamless integration with existing distribution networks and PONs and thus paves the way for future mobile front- and backhaul architectures.**

***Index Terms*—Radio-over-fiber, millimeter-wave communications, W-band wireless, microwave photonics, small form factor pluggables.**

I. Introduction

THE increasing use of bandwidth intensive applications—such as high definition video streaming and holographic video conferencing—on consumer devices has created a large demand for high-speed mobile and wireless connections. To enable these, a transition away from the already crowded and congested conventional wireless bands is necessary and millimeter wave (mm-wave) frequencies in the IEEE V- and W-bands (40–75 GHz and 75–110 GHz) are seen as prime candidates [1]–[4]. While the region around 60 GHz has received major attention with regards to indoor wireless distribution [2], frequencies at 71–76 GHz and 81–86 GHz—commonly referred to as E-band after the corresponding waveguide band—are the prime candidates for medium and long distance mm-wave wireless links, due to the lower atmospheric absorption [2] and the large continuous spectrum allocations for wireless communications [5], [6].

Supporting the density and data rates envisioned for the coming generations of mobile networks will require major changes to front-, mid- and backhaul architectures for radio access units (RAUs) [5] and thus to the way the latter are connected to and integrated with the core infrastructure. Additionally these new front-, mid- and backhaul links must seamlessly tie in with existing optical distribution networks such as passive optical networks (PONs) [1], [7]. Radio-over-fiber (RoF) links in the mm-wave range stand out as prime candidates since they combine the relatively large available bandwidths in the mm-wave bands with the easy optical distribution over significant fiber distances [1], [8].

Mm-wave photonic wireless links have been demonstrated in a number of configurations [6]–[13], of which heterodyning of two independent lasers for photonic upconversion is one of the most promising for integration with existing optical distribution infrastructure [7]. However in order to make these truly feasible they do not only need to easily integrate with already deployed systems, but also need to be based on technology already used therein, such as enhanced small form-factor pluggable modules (SFP+) [7].

In [13] a W-band photonic wireless link based on a commercial SFP+ module was demonstrated, enabling seamless integration with existing optical distribution networks based on SFP+ modules, such as PONs and wavelength division multiplexing (WDM) point-to-point links. The radio frequency (RF) signal is generated through heterodyne photonic upconversion with an independent laser as local oscillator. This was, to the best of our knowledge, the first SFP+ based W-band transmission and at 2.5 Gbit/s achieved an outdoor wireless distance of 225 m. In this letter we discuss the link and setup in more detail and give a calculation of the maximum achievable distance with increased transmission power, using readily available mm-wave RF equipment and showing wireless distances in excess of 2 km to be within reach.

The letter is structured as follows: section II describes the SFP+ based setup and section III discusses the experimental results, including analysis of the frequency stability of the generated RF signal (III-A), transmission performance for wireless distances of 100–225 m (III-B) and evaluation of the maximum wireless range of the presented setup (III-C). Section III-D gives a short discussion of the results, before finally section IV summarizes and concludes the letter.

II. SFP+ Based W-Band Transmission Setup

The SFP+ based W-band transmission setup is depicted in Fig. 1 and consists of three sections which in a deployment

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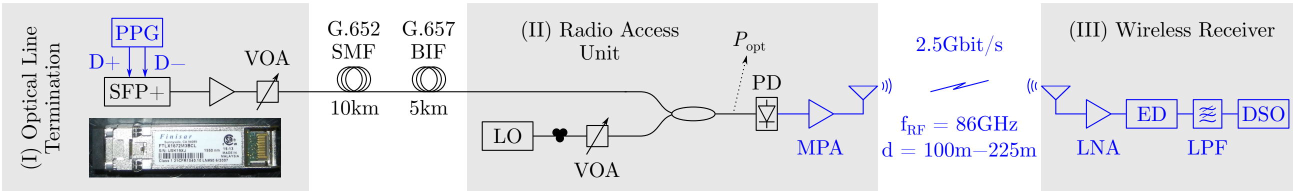

Fig. 1. Experimental setup for hybrid photonic wireless transmission. SFP+: enhanced small form-factor pluggable, PPG: pulse pattern generator, VOA: variable optical attenuator, LO: local oscillator, PD: photodiode, MPA: medium power amplifier, LNA: low noise amplifier, ED: envelope detector, LPF: Low-pass filter, DSO: digital storage oscilloscope.

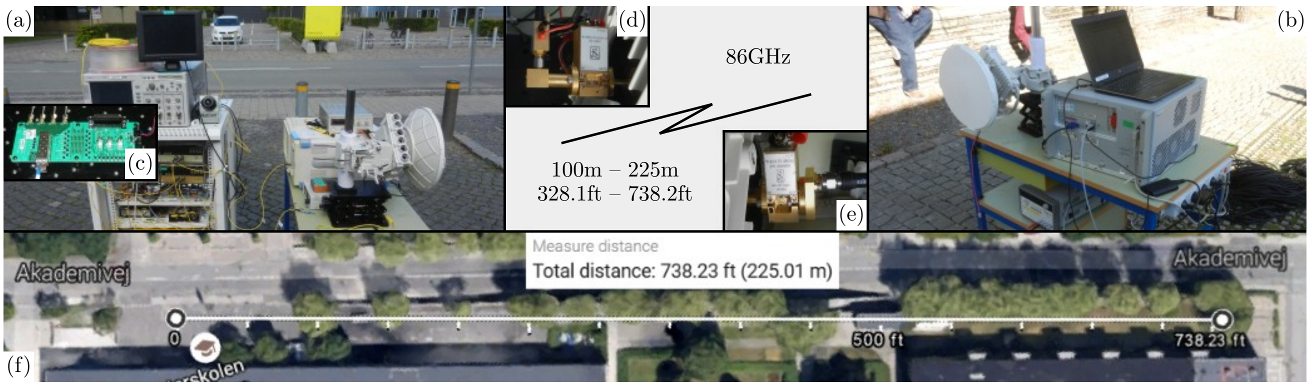

Fig. 2. Outdoor experimental setup: (a) transmitter station, (b) receiver station, (c) evaluation board with SFP+, (d) PD and MPA mounted on transmit antenna, (e) LNA and ED mounted on receive antenna, (f) geographic overview of experiment location and wireless transmission path.

case would be geographically separate:

(I) *Optical Line Termination*: generates the optical signal, based on a commercial enhanced small form-factor pluggable (SFP+). Linked by optical fiber transmission to
(II) *Radio Access Unit*: performs optical to radio-frequency conversion and allows W-band wireless transmission to
(III) *Wireless Receiver*: receives the W-band signal and downconverts it to baseband.

The outdoor experimental setup is shown in Fig. 2 and consists of a transmitter station—where optical line termination (OLT), fiber transmission and radio access unit (RAU) are co-located—and a receiver station. The optical signal is generated using a SFP+ module (Finisar FTLX1672M3BCL), which includes a limiting driver and is fed a 2.5 Gbit/s $2^{15}-1$ bit long pseudo-random bit sequence (PRBS15) non-return-to-zero (NRZ) signal from a pulse pattern generator (PPG). The output of the SFP+ has an extinction ratio of 9 dB and 0 dBm optical power. The signal is amplified and transmitted through a combination of 10 km ITU-T G.652 standard single-mode fiber (SMF) and 5 km ITU-T G.657.B3 bend insensitive fiber (BIF), representing a typical optical link and allowing for the inclusion of BIF for on-site installation and antenna feeding.

For optical to RF conversion an external cavity laser (ECL) acts as a tunable local oscillator (LO) for heterodyne photonic upconversion on a photodiode (PD). The optical input power P_{opt} incident on the PD is controlled through two variable optical attenuators (VOAs), allowing separate adjustment of signal and LO powers. The RF signal is amplified by 8 dB using a medium power RF amplifier (MPA) before being transmitted over 100–225 m using a pair of parabolic antennas with a gain of 48 dBi each.

At the receiver station a low noise amplifier (LNA) provides 40 dB gain before the signal is downconverted using a Schottky diode based W-band envelope detector (ED) with a nominal 3 dB bandwidth of 3 GHz. A low pass Bessel filter with a 3 dB cutoff frequency of 1.8 GHz limits noise bandwidth before the signal is recorded on a digital storage oscilloscope (DSO) to determine received signal quality and for offline error counting to estimate bit error rates (BER).

The suggested setup minimizes cost and complexity in the optical domain by using heterodyne photonic upconversion and by employing a commercial SFP+ for signal generation, which further allows easy integration with existing deployed infrastructure. The use of envelope detection allows a simple RF setup at the receiver, while the RF transmitter requires only a single MPA.

III. Experimental Results

A. Frequency Stability of the Generated mm-Wave Signal

Frequency stability of the RF signal is a requirement in any wireless transmission and thus the stability of the signal generated with the SFP+ based setup has been analyzed. With a free running laser as LO and no tracking of signal wavelength, any wavelength drift of the two involved lasers may result in a frequency drift of the generated RF signal and thus spectra of the optical signal just before upconversion have been recorded over 12 h at intervals of 30 s. Fig. 3 (a) shows the recorded spectra over time, while Fig. 3 (b) and (c) show laser powers and frequencies; Fig. 3 (d) finally shows the frequency of the generated RF carrier over time. Power stability of the lasers is found to be within ± 0.3 dB of the power levels set, while on the laser wavelength a small drift is observed after power

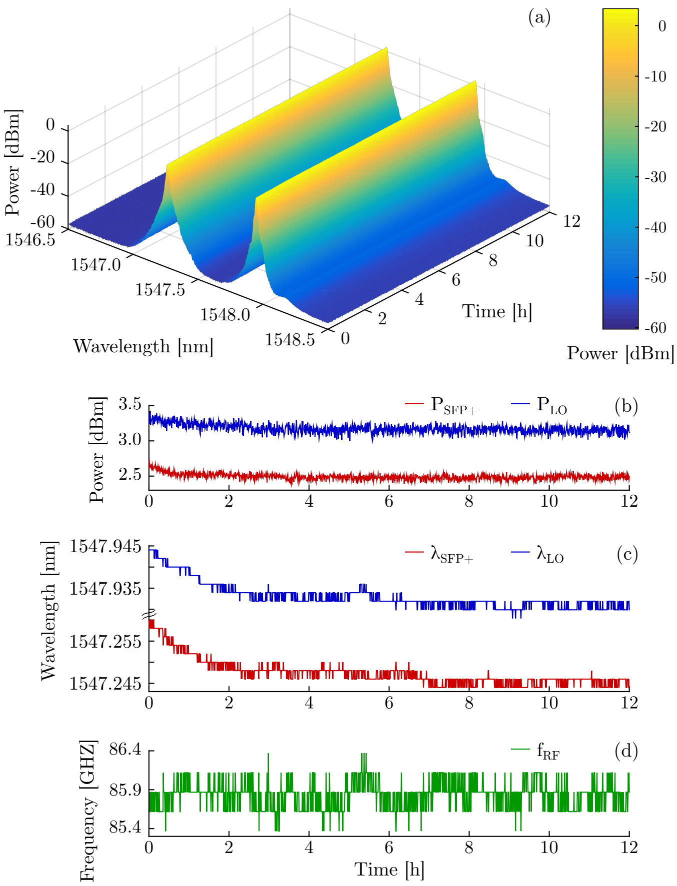

Fig. 3. SFP+ and LO laser power and wavelength and resulting RF carrier frequency stability over 12 h: (a) recorded spectra, (b) laser powers, (c) laser wavelengths, (d) RF carrier frequency.

on, stabilizing to variation within ±0.02 nm after ca. 2 h. With both lasers only featuring basic in-package cooling, similar or better stability may be achieved with improved temperature control, even if signal generation and upconversion take place under different ambient conditions.

The resulting RF carrier is found to vary by less than ±0.5 GHz across the whole 12 h period, despite the wavelength drift observed after power on. While clearly above the ±150 ppm recommended by the ITU-R [14], such a variation may be acceptable for a highly directive point to point transmission link with a large bandwidth and is found to not affect the presented system. To adhere to ITU-R recommendations, setups based on a single laser are likely to be required [15] and thus a trade-off between complexity, easy integration with PON systems and RF frequency stability needs to be found.

B. Outdoor W-Band Wireless Transmission Results

W-band wireless transmission is performed outdoors on the university campus over distances of 100–225 m. The optical power incident on the photodiode P_{opt} is set to 5 dBm and the received signal quality is monitored in distance steps of 25 m. Transmission was found to be error free at all distances with recorded sequences of a total length >25 Mbit, suggesting a BER on the order of 10^{-7} or lower. Calculation of the Q factor of the received signals and estimating BER as:

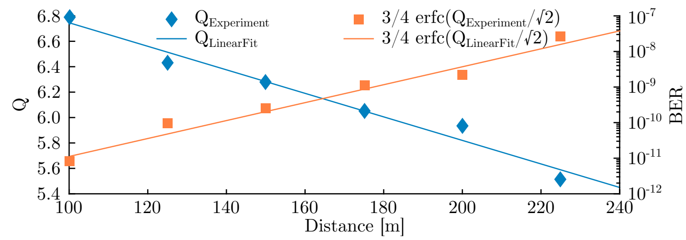

Fig. 4. Observed Q factors and derived BER estimates after 225 m wireless transmission of a 2.5 Gbit/s signal on an 86 GHz carrier.

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} \tag{1}$$

$$BER \approx 3/4 \mathrm{erfc}\left(Q/\sqrt{2}\right) \tag{2}$$

(where μ_0, μ_1 are the mean values of the signal levels and σ_0, σ_1 their standard deviation) finds an estimated BER of 2.6×10^{-8} at 225 m and even lower error rates for shorter distances, confirming the performance estimate derived from observing no errors. This confirms the viability of using a SFP+ in RoF links despite its larger linewidth and lower extinction ratio and suggests higher order amplitude modulation formats to be possible if an SFP+ with linear drivers is used.

Fig. 4 plots the obtained Q factors over distance alongside resulting BER estimates, suggesting a linear relation with distance and thus the system to be limited by available transmitter power and additive white Gaussian noise. They further confirm and adhere to expectations derived from previous experiments in similar conditions [8] and that due to its high directivity the link may be considered practically line-of-sight, even at 225 m wireless distance.

C. Maximum Achievable Wireless Distance

Further comparison of transmission performance with that found in [8] where a similar setup—in particular the same receiver—was employed, allows estimation of the maximum achievable distance for a system limited by the available RF transmitter power. From the photocurrents observed at the optical to RF conversion stage the RF signal level P_{PD} generated by the PD at a reference optical power of $P_{\mathrm{opt}} = 5\,\mathrm{dBm}$ is easily estimated and found to be −9 dBm. Together with the antenna gains and the loss observed in the wireless channel this allows an estimation of the receiver sensitivity.

Assuming line of sight transmission, the loss in the wireless channel L can be estimated as the sum of free space propagation loss L_{FS} following the Friis' model and the atmospheric absorption L_{A} [2], [4]:

$$L_{\mathrm{FS}} = 10\log\left(\left(4\pi df/c\right)^2\right) = 20\log\left(4\pi df/c\right) \tag{3}$$

$$L = L_{\mathrm{FS}} + L_{\mathrm{A}}d = 20\log\left(4\pi df/c\right) + L_{\mathrm{A}}d \tag{4}$$

where c is the speed of light in vacuum, f the carrier frequency and d the transmission distance; an atmospheric absorption L_{A} of 0.2 dB/km for transmission at 86 GHz [2] is used for receiver sensitivity and maximum distance estimations. The received power P_{Rx} at the output of the receiver antenna is then easily estimated from the generated RF power P_{PD}, the

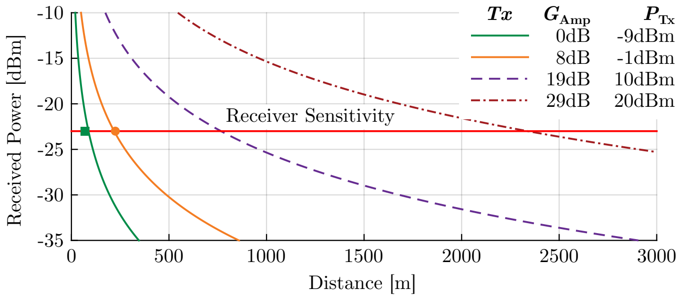

Fig. 5. Received powers over distance for different RF transmitter configurations; ■: experimental data from [8], ●: experimental data in this letter.

amplifier gains at the transmitter G_{Amp}, the antenna gains G_{Tx} and G_{Rx} and the attenuation during transmission L:

$$P_{\mathrm{Rx}} = P_{\mathrm{PD}} + G_{\mathrm{Amp}} + G_{\mathrm{Tx}} - L + G_{\mathrm{Rx}} \tag{5}$$

With Eq. (5) the values from this letter and those of [8] independently yield a receiver sensitivity of −23 dBm.

With the receiver sensitivity known, the maximum wireless reach of the system can be estimated, depending on the received optical power and the RF amplifier configuration at the wireless transmitter. Fig. 5 shows received power over distance for a number of amplifier configurations and Table I compares the corresponding radiated powers and maximum achievable distances. The calculated distances of 85–2340 m fit the experimentally demonstrated distances of this letter and [8] and suggest distances in excess of 2 km to be reachable with only two amplifiers required at the transmitter and while maintaining the same low complexity Schottky diode based wireless receiver. It should be noted however that for links of such distances, multipath propagation and associated fading may come in to effect [4], making the link no longer line-of-sight as considered in [8] and this letter.

D. Discussion

Using the signal from a standard commercial SFP+, the presented system is designed to use equipment already deployed in distribution networks such as PONs. With a free running laser as local oscillator it enables hybrid RAUs for mobile front-, mid- and backhaul, while demonstrating seamless integration beyond that of [7]. The system combines a commercial SFP+, a free running LO for up- and envelope detection for downconversion to offer a radio-over-fiber link with high capacity, large wavelength drift tolerance and seamless integration with existing optical distribution networks.

Analysis of transmission performance shows bit error rates below 10^{-6} at a wireless distance of 225 m and evaluation of the maximum wireless reach of the proposed system shows wireless links of up to 2340 m to be possible. The system achieves sufficient frequency stability to allow reliable transmission of a 2.5 Gbit/s signal, despite allowing both lasers to drift freely. Allowing a guard band of 1.5 GHz between channels, this suggests an availability of 5 channels in the lightly licensed W-band. With 15 km of fiber transmission included in the experiment this demonstrates that the reach necessary for future front-, mid- or backhaul links can be achieved with readily available technology.

TABLE I
MAXIMUM ACHIEVABLE WIRELESS DISTANCE

Amplifiers	P_{PD} [dBm]	G_{Amp} [dB]	P_{Tx} [dBm]	d_{Max} [m]
none	–9	0	–9	85
MPA1	–9	8	–1	220
LNA	–9	19	10	770
LNA+MPA2	–9	29	20	2340

IV. CONCLUSIONS

In this letter a hybrid photonic wireless link based on a commercial SFP+ module and employing heterodyne photonic upconversion has been demonstrated. Experimental analysis includes frequency stability measurement of the generated RF signal and wireless transmission over distances up to 225 m at data rates of 2.5 Gbit/s with (BER) $< 10^{-6}$. Wireless distance is found to be limited only by the available transmitter RF power and calculation of the maximum achievable distance with typical RF amplifiers at the transmitter yields a wireless reach of well above 2 km, confirming the potential of long distance mm-wave links.

The presented system setup based on a commercial SFP+ module offers seamless integration of hybrid W-band radio access units into existing optical distribution schemes, such as PON and WDM point-to-point links based on standard commercial SFP+ modules.

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